A CATHETER TIP HOT WIRE ANEMOMETER BLOOD FLOWMETER

by

Robert Kenneth Pollak

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ROBERT KENNETH POLLAK

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Robert Kenneth Pollak

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ABSTRACT

The problem of determining blood flow rates in the major veins and arteries of the body has been under investigation for several years. The use of a catheter appears to be a promising method of determining the blood flow since catheterization is relatively simple and fast. The requirements for the sensor led to the use of constant temperature hot wire anemometer as the transducer to be mounted on the catheter. The electronic circuit consisted of a D.C. bridge with A.C. feedback to the hot wire. The device was constructed and tested. Results showed that the zero to 100 cps response which is required for blood flow measurement was attained and that the instrument was practical.

Thesis Supervisor: William D. Jackson
Title: Associate Professor of Electrical Engineering

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The turntable used for calibrating the instrument was constructed in the Research Laboratory of Electronics Machine Shop and the catheter probe was constructed at the Lemuel Shattuck Hospital in the office of Dr. Sear.

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LIST OF SYMBOLS

a	constant
b	constant
c	constant
cps	cycles per second
D	diameter
d	constant
f	frequency
H	Heat
k	Thermal conductivity of fluid
I	current
Nu	Nusselt number
Pr	Prandtl number
R	Resistance
Re	Reynold's number
T	Temperature of Hot Wire
T_f	Temperature of fluid
V	Velocity
α	Temperature coefficient of Resistance
ρ	Density of Hot Wire material
γ	Specific Heat of Hot Wire material
τ	Thermal Time constant
ν	Viscosity

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CHAPTER I INTRODUCTION

1.1 Background

The development of methods for the accurate measurement of pulsatile blood flow in surgery, clinical research, and animal experiments has been under investigation for some time. The instantaneous velocity measurement of blood flow in veins and arteries at various locations in the body is required to provide information to physicians and medical researchers. All current methods of blood flow determination, as reviewed by Wetterer,[10] have inherent imperfections or restrictions. The devices presently available can be divided into two groups. The first group is those devices which are implanted by surgery and the second group includes those devices which can be used without major surgery. Devices in the first group are inherently inconvenient since they can only record at one site until repositioned surgically, and considerable time delay is required to implant the device and allow for post operative recovery. The most successful device of this group is the electromagnetic flowmeter which is commonly regarded as the standard for blood flow measurements. Most other schemes, such as venture, pitot tube, pressure gradient, bristle pendulum, ultrasonic transit time, and ultrasonic doppler shift, must be considered as belonging to group

one if recordings of other than near skin areas are desired.

There are very few non-operative methods available for the continuous recording of pulsatile flow. Venous-occlusion plethysmography[10] permits short time recordings in limbs, fingers, and toes. Another method which is being investigated is the catheterization of blood vessels and heart.[5] Interest in this method is mainly due to the simplicity of insertion, and the ease and speed of relocation. Katsura,[5] Marble,[6] Thompson,[9] and Pruslin[8] have tested and/or constructed catheter tip blood flowmeters using thermistors. These studies have shown that using the smallest available thermistors in detection instruments resulted in time constants of about one half second even when using feedback. Research is continuing in this field and time constants of 20 milliseconds are presently being obtained by Marble. The long time constant is due to the long thermal time constant of the thermistors. Wetterer[10] and Ferguson[2] have shown that the accurate measurement of pulsatile blood flow in humans requires a frequency response of at least 52 cps and in particular cases may be extended to 100 cps. The use of thermistors at this time is therefore limited to mean flow measurements due to their poor frequency response. However, the use of a hot wire anemometer is an interesting possibility since this device has been used successfully in air to study

velocity fluctuations of several kilocycles per second. To determine if the use of a hot wire in blood is promising, it is necessary first to determine the thermal time constant of a hot wire in this environment.

1.2 Thermal Time Constant of Hot Wire

The thermal time constant, τ, of the wire is calculated using the formula given by Janssen, et al.,[4] and data from the manufacturer (Sigmund Cohn Company) and engineering materials reference books.[1] The formula for the thermal time constant is

$$\tau = \left(\frac{\pi}{4}\right)^2 D^4 \beta \gamma \frac{T-T_f}{\alpha I^2}$$

Therefore, to obtain a short time constant, it is necessary to keep the wire diameter small and the current high. The smallest wire size that can be handled using standard tools is one mil diameter wire. The maximum current that can be used in this wire in still water is about 400 milliamperes. Nickel was picked as the material for the wire since this metal has the highest temperature coefficient of resistivity of common metals and can be drawn into fine wire. The thermal time constant can now be calculated using

$D = 2.54 \times 10^{-5}$ meters

$\beta = 8.85$ G per Cu Cm

γ = .112 G - cal per g.

$T - T_f$ = 20 degrees c

α = .00672 ohms/ohm/°c

I = 100 milliamperes

which gives the value

τ = .542 milliseconds

The maximum frequency response that the wire is capable of is

$$f = \frac{1}{2\pi\tau} = 294 \text{ cps}$$

This is greater than the maximum desired frequency response of 100 cps. The one mil wire therefore appears satisfactory.

The thermal time constant calculated above is for a bare wire. Since the wire is to be operating in a conducting fluid consideration of the current leakage path is required. An exact solution of this problem is quite lengthy, however, as a rapid check of the magnitude of the problem, an approximation is made using two parallel plates. In this model, the plates are spaced a distance apart equal to the spacing between the wire ends. The area of each plate is 100 times the wire cross sectional area. The conductance of human blood is given by Mungall, Morris, and Martin[7] as 0.325 Mho/Meter at most. The resistance of the leakage path of the model calculated using this value is 247 ohms compared

to a wire resistance of 1.265 ohms. Thus, the use of a bare wire, which will give highest speed of response, is permissible.

1.3 Probe Selection

The problems associated with the construction of a hot wire anemometer blood flowmeter logically fall into three areas:

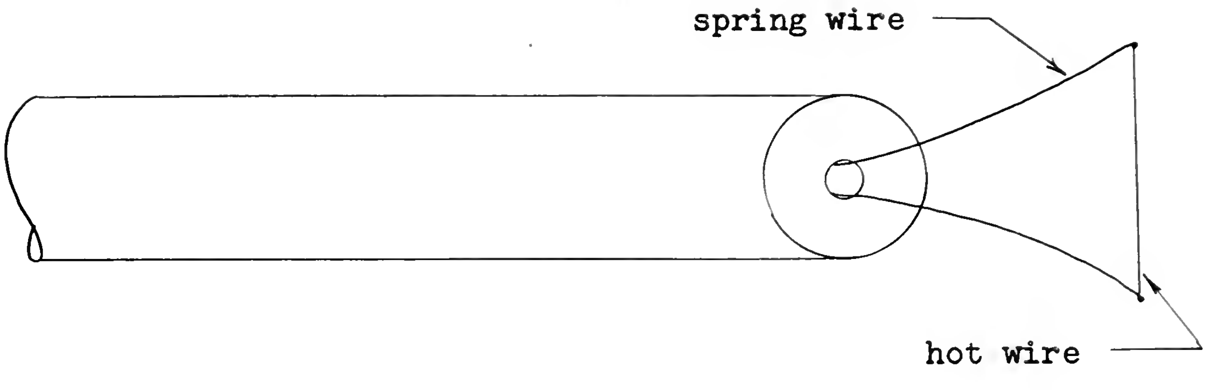
1. the design and construction of the actual velocity sensing probe,
2. the design and construction of the related electronic circuits, and
3. the calibration and testing of the instrument.

The probe design is taken up first since the requirements placed on the probe make it less flexible than other parts of the system. Ideally, the probe would be easy to insert into the blood stream, would be readily moved about, and would not disturb the flow that is being measured. The diameter of the hot wire should be as small as possible since the amount of heat put into the blood stream by the wire is a function of wire size. Naturally, a high heat input to the blood is undesirable. Furthermore, the flowmeter is to be used internally near, possibly in the heart where stray electrical signals must be kept to a minimum. The amount of current fed to the wire for a given amount of heating is dependent on wire surface area and electrical

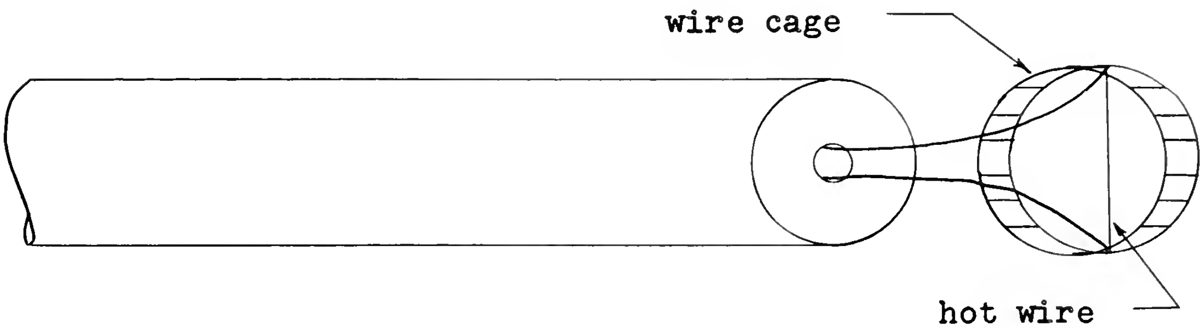
resistance which again dictates small wire size. In addition, to keep the thermal time constant of the wire short, the wire diameter must be kept small.

As mentioned previously, the requirements placed on the probe led to the use of a cardiac catheter. This device is easily inserted into the blood stream and can be repositioned readily and accurately using X-ray techniques since the catheter is filled with a material that is opaque to X-rays. The catheter selected was two millimeters in diameter which restricted its use to the major arteries and veins of the body where two millimeters is small compared to channel diameter. This restriction was accepted since knowledge of blood flow even in these areas is limited.

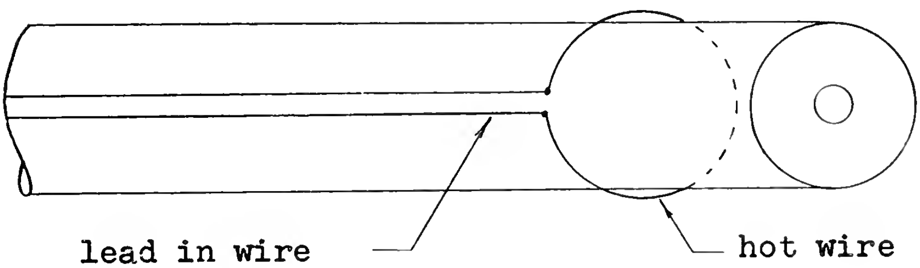
The choice of placement of the hot wire in the fluid stream led to some interesting possibilities. A few of the designs considered are shown in Figure 1. Design A has the advantage that the hot wire is placed in the stream similar to the method used in wind tunnels. The wire is located upstream from the catheter probe and therefore, the probe does not disturb the flow before measurement is made. However, it was found that this design had several major disadvantages from a practical standpoint. First, the hot wire tended to position itself against the wall of the channel. Secondly, the movement of the wire into position ahead of the probe usually resulted in a broken hot wire. Third, the positioning wires leading through the center hole of



Design A



Design B



Design C

FIGURE 1. Proposed Probe Construction Designs

the catheter obstructed this hole, preventing its use for pressure readings. It is anticipated that simultaneous pressure and velocity measurements will be taken and the center channel of the catheter could be conveniently utilized for the transmission of the pressure.

Design B is a technique which places the hot wire in a cage that prevents the wire from resting against the side of the channel. This method has the other disadvantages of design A, and the increased complexity of construction causes increased probability of failure by breaking.

Design C was finally selected as the design to be used. This design has the disadvantages that the probe disturbs the flow before measurement and the hot wire is in the developing boundary layer. Furthermore, the hot wire is in close proximity to the catheter which effects the heat transfer characteristics. These disadvantages can be accepted since the calibration is to be obtained experimentally. The predicted calibration may be different than actual calibration due to these factors.

This design was selected mainly for its ruggedness. Details of construction are shown in Figure 2 and Figure 3. Two wires are wound around the catheter to provide automatic ambient blood temperature compensation as discussed in a later chapter.

A method was required to position the catheter in the center of the stream. It was found that if the catheter

HOT WIRE PROPERTIES

Material	-	Nickel
Diameter	-	0.001 in.
Length of one turn	-	0.0206 ft.
Resistance	-	38.7 ohms/ft.
Resistance per turn	-	1.265 ohms.
Temp. coef. of resistivity		.00672 ohms/ohm/°c
Thermal time constant	-	.542 ms

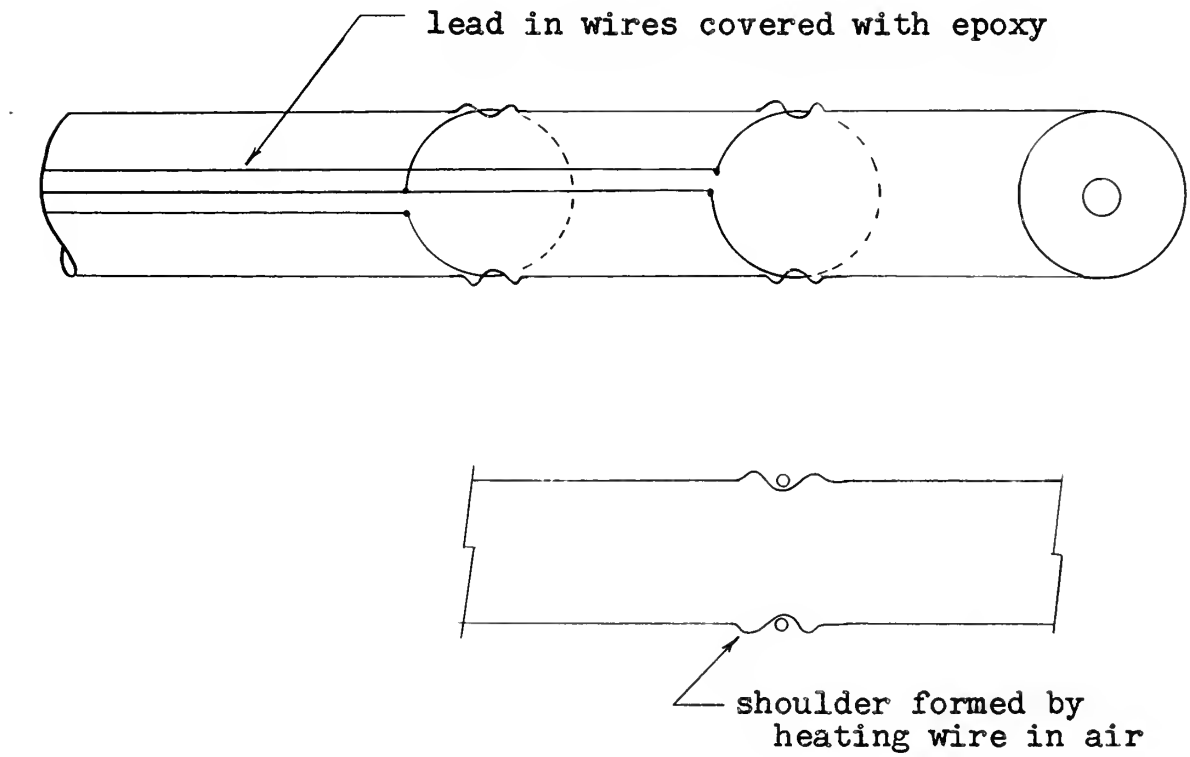


FIGURE 2. Details of Probe Construction

FIGURE 3. The Assembled Catheter Probe

was heated in hot water it could be formed into a helix ahead of and following the point where the hot wire was wound around the catheter. When repositioning a catheter, standard usage practice provides for a wire to be run down the center hole of the catheter to provide additional stiffening. When this wire is inserted into the catheter which is formed into a spiral, the wire stiffness is sufficient to straighten out the catheter. The catheter is then placed in the desired position, and the wire is withdrawn, allowing the catheter to spring back into the spiral configuration. By careful design, this places the hot wire segment of the catheter in the center of the stream for a small range of vessel diameters. The spring action also tends to force the flexible wall of the channel outward, providing a more constant channel diameter during the pulsations of pressure. Fluid flow can then be more accurately equated to velocity measurement.

The copper lead in wires are relatively large in diameter, 10 mil, so that their thermal resistive contribution is small. In addition, the lead in wires are covered with epoxy to insulate them electrically and thermally. No material was found which would adhere well to the polyethylene catheter but the epoxy will work satisfactorily if not left in a liquid for more than a few hours. The fine nickel wire is wound once around the catheter and then 100 milliamperes are applied while the catheter is in air. This current heats the polyethylene catheter to melting temperature

without burning out the wire. The polyethylene flows away from the wire forming a shoulder that protects the nickel wire during insertion through the skin and leaves the wire almost completely free of contact with the catheter (See Figure 2). The temperature dependent change of resistance of the wire and hence the size of the voltage signal to be detected could be increased by additional turns of wire around the catheter, but this would cause the heat transfer rate of downstream wire to be effected by the heat lost to the fluid by the upstream wire. It was found that the single turn of wire provided sufficient signal so that additional turns of wire were not required.

1.4 Heat Transfer Equations

Measurement of fluid flow with a hot wire requires knowledge of the heat transfer equations applicable to the wire and the fluid to be used. Very little data is available concerning the properties of interest of human blood. The blood is known to be non-neutonian on a microscopic level, consisting of long stringy solids in suspension. On a macroscopic level, which is the area of interest in this study, the blood properties are approximated by the properties of saline.

The equation for heat transfer from a hot wire into the surrounding fluid is basically King's equation[4]

$$H = (a + b\sqrt{v})(T - T_f)$$

where the constants a and b are dependent on the properties of the wire and the fluid. Another form of this equation which is more suitable for calculation is given by Grant[3] as

$$H = \pi k \quad Nu(T - T_f)$$

where $Nu = c + d\sqrt{Re}$ = Nusselt number Grant points out that the value of c is in dispute but that it has been established as very close to .3 while $d = d(Pr)$

For saline $Pr = 9$

Therefore, from Figure 1 in Grant[3], the value of d is

$$d = .9$$

The Reynolds number must now be calculated

$$Re = \frac{VD}{\nu}$$

where

$$\nu = 10^{-5} \ ft^2/sec$$

$$D = .834 \times 10^{-4} \ ft$$

Therefore

$$\sqrt{Re} = 2.9\sqrt{V}$$

$$Nu = .3 + 2.58\sqrt{V}$$

The other values are established at

$$D = .834 \times 10^{-4} \ ft$$

$$k = .35 \ \frac{BTu}{hr \ ft \ °F}$$

Substitution of all values, and converting to watts gives

$$H = (.00198 + .0170\sqrt{V})(T - T_f) \ \text{watts}$$

where V varies from zero to 4.6 feet/sec (140 cm/sec).

The electrical power converted into heat in the wire is

$$H = I^2R$$

It only remains to equate the two equations for heat to derive the desired relationship between current and velocity

$$I = \sqrt{\frac{1}{R}\ (.00198 + .0170\sqrt{V})(T - T_f)}$$

where R = 1.265 ohms.

CHAPTER II PROCEDURE

2.1 Amplifier Design

The selection of the feedback amplifier design required consideration of the signal size and the required feedback current. To detect the signal, the hot wire was placed in a bridge circuit where the change in resistance due to change in temperature would correspond to a voltage error signal. Having established the wire characteristics, the magnitude of this voltage signal depends on the bridge current and the change in wire temperature from the ambient (zero velocity) operating value.

The maximum allowable temperature change was selected as one degree. A value of 100 milliamperes was established as the maximum value that could be used in the bridge. It was found that operating the bridge current at greater than 100 ma tended to produce sufficient heating such that the undesirable results of a constant current operation hot wire anemometer occured in the ambient temperature sensing arm of the bridge. These values resulted in the size signal to be detected of

$$\Delta V = I\,(\Delta R) = I(\alpha)(R)(\Delta T)$$

$$= (100 \times 10^{-3})(.006)(1.265)(1)$$

$$= .76 \text{ mv}$$

which is readily attainable.

Selection of the amplifier to be constructed was basically governed by the desire to have an ambient temperature compensation arm in the bridge. The feedback current to the hot wire had to be isolated from this arm, and the use of a D.C. bridge with A.C. feedback provided a method of achieving this isolation using capacitors and inductors. The usual type of feedback used in wind tunnels, etc., consists of a feedback loop using only D.C. However, in these applications, the ambient temperature can be accurately established. For humans, it is known that the temperature of the blood varies from person to person, site to site, and day to day. Measuring this temperature at each point would be difficult and time consuming. The ability to have automatic ambient temperature compensation is therefore desirable, and the use of a second wire in the bridge provides this feature.

The initial amplifier design is shown in Figure 4. The two wires that form one half of the bridge are mounted on the probe. The out of balance signal from the D.C. bridge is amplified by the D.C. chopper stabilized amplifier and sent to the grid of the following tube. The current flow in this half of the tube changes the bias on the tube, amplitude modulating the 2 kc signal. The modulated 2 kc signal is then amplified and sent to a power amplifier tube which provides the AC current that is fed back to the hot wire.

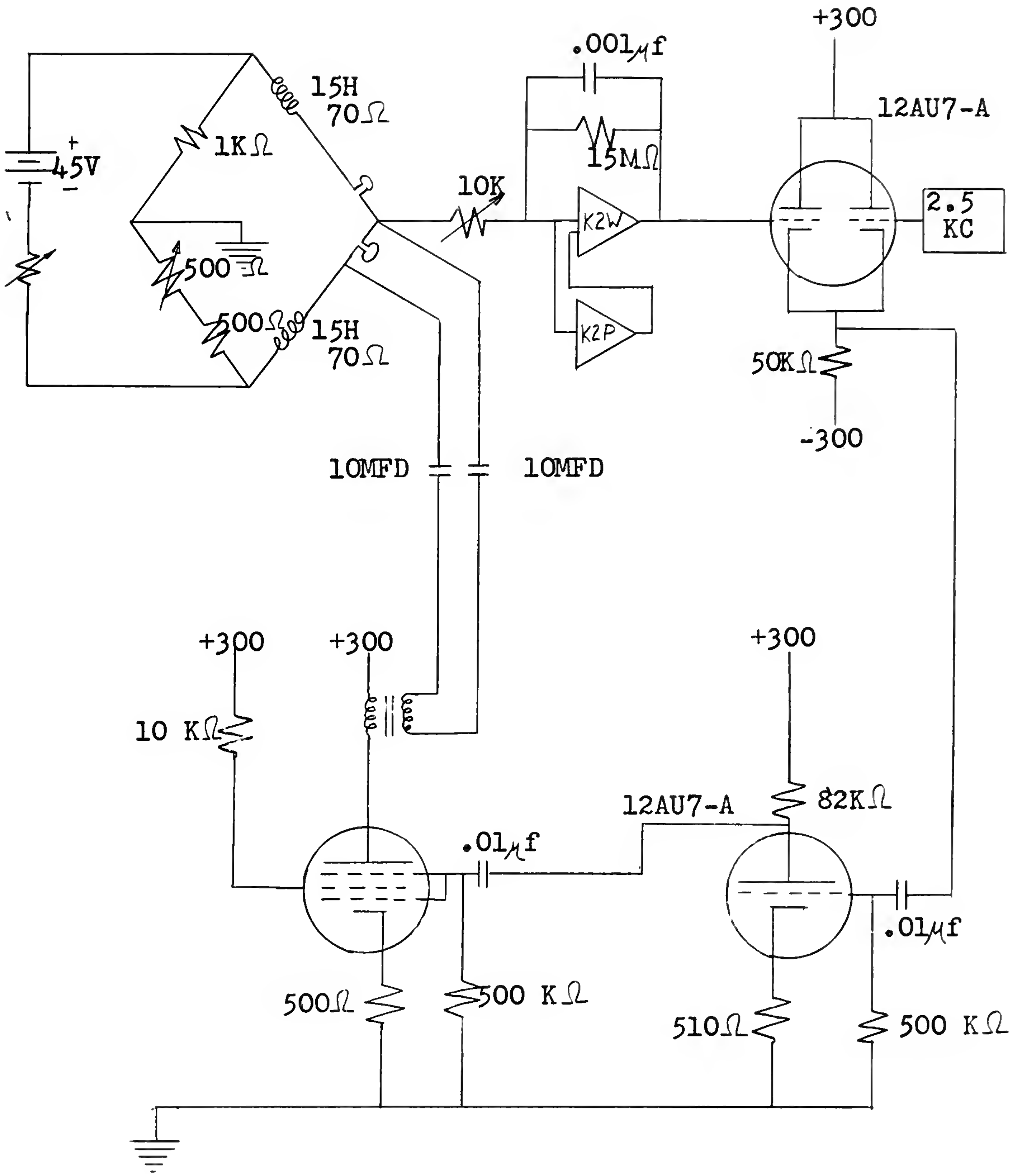


FIGURE 4. Initial Circuit Design

The D.C. amplifier had a frequency response of 0 - 100 cps and therefore did not pass the 2 kc signal. The transformer was required in order to isolate the + 300 volt power supply from the probe which is to be used internally.

After constructing this circuit, it was tested and the following defects became apparent: The K2P choppers introduced a triangular voltage wave of the order of 1 volt into the output of the D.C. amplifier, and the maximum A.C. current attainable was 400 ma. Additional current was attained by adding a second power tube. The manufacturer of the K2P (Philbrick) was consulted but the noise problem was not resolved. Replacing the K2P with power supply bias resulted in excessive drift. Battery bias was attempted and proved to be relatively successful. Elimination of 60 cps noise required care in shielding and avoidance of ground loops. The two large inductors picked up the 60 cycle noise very greatly and a 60 cycle notch filter was required to eliminate this problem.

D.C. amplifier drift was the final problem to be solved. A Kintell model 111 BFO Chopper stabilized operational amplifier was obtained that had the necessary specifications. There was some noise due to microphonics but in general, this amplifier was adequate. It was noticed that some drift in the output of the D.C. amplifier which was originally attributed to the amplifier was later identified as bridge battery voltage drift. A number of batteries

were installed in parallel to minimize this source of noise. The final circuit design is shown in Figure 5.

2.2 Experimental Procedure

The usual method of testing flowmeters has been to place the flowmeter in a flow loop. Considerable time was required to construct and calibrate a flow loop so it was decided in this case to calibrate the flowmeter using a turntable. A large container was mounted on the turntable and a test probe was positioned accurately in the container with a fixed support. The container was filled with water and rotated at various speeds by means of a variable speed A.C. motor. The speed of rotation was determined using a strobe light and a stop watch.

The probe was placed in still water and the calculated zero velocity current, 178 ma, was set by adjusting the variable resistor in the bridge circuit. The turntable was then rotated until the water was flowing by the probe at 140 cm/sec and the calculated required current of 755 ma was obtained by adjusting the input resistance of the D.C. amplifier which determined the gain of this stage. This process was continued until the two end points (zero velocity and 140 cm/sec) produced the desired feedback currents without further adjustments. Other points on the calibration curve, Figure 6, were then obtained by adjusting the speed of the turntable.

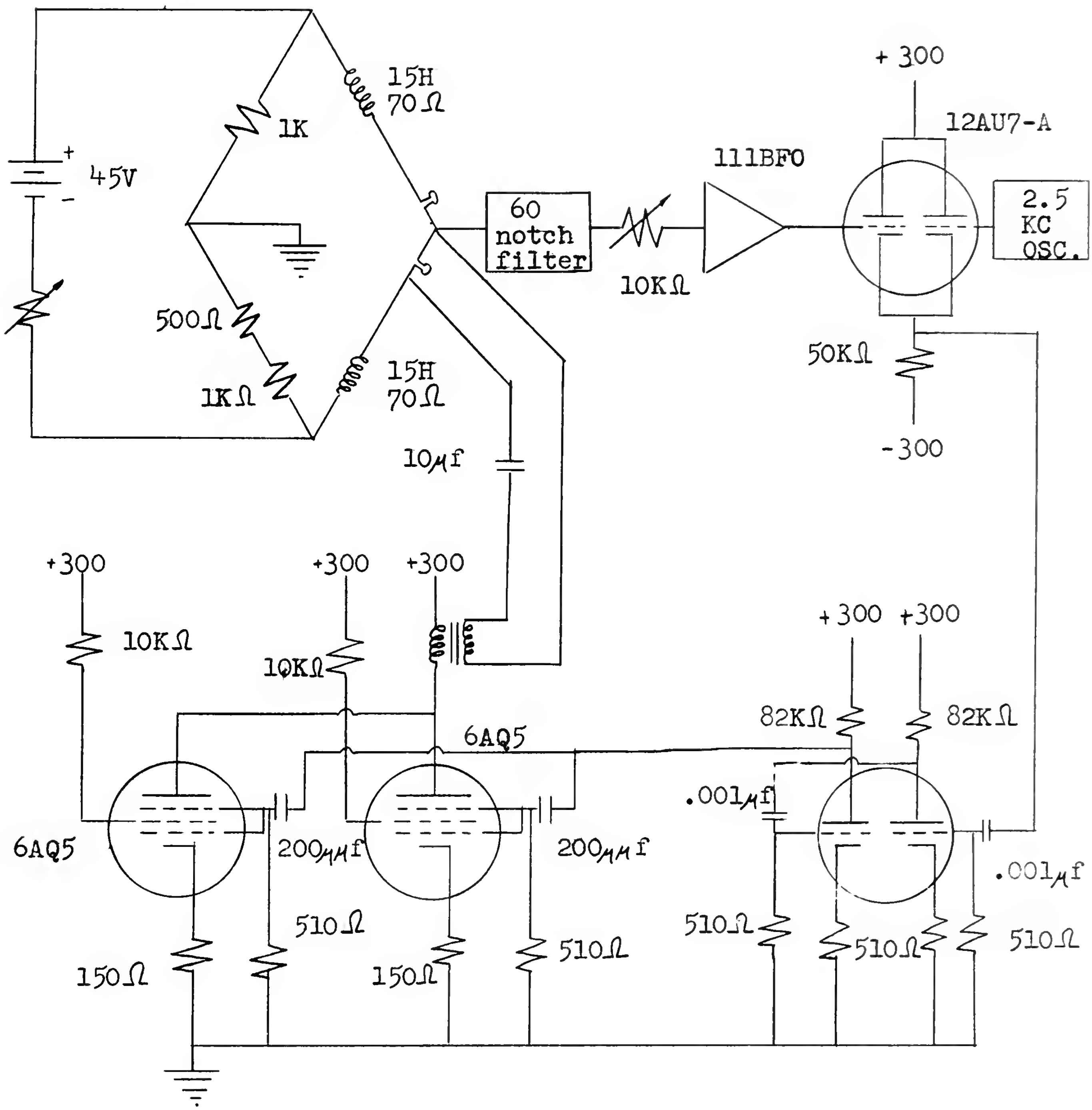


FIGURE 5. Final Circuit Design

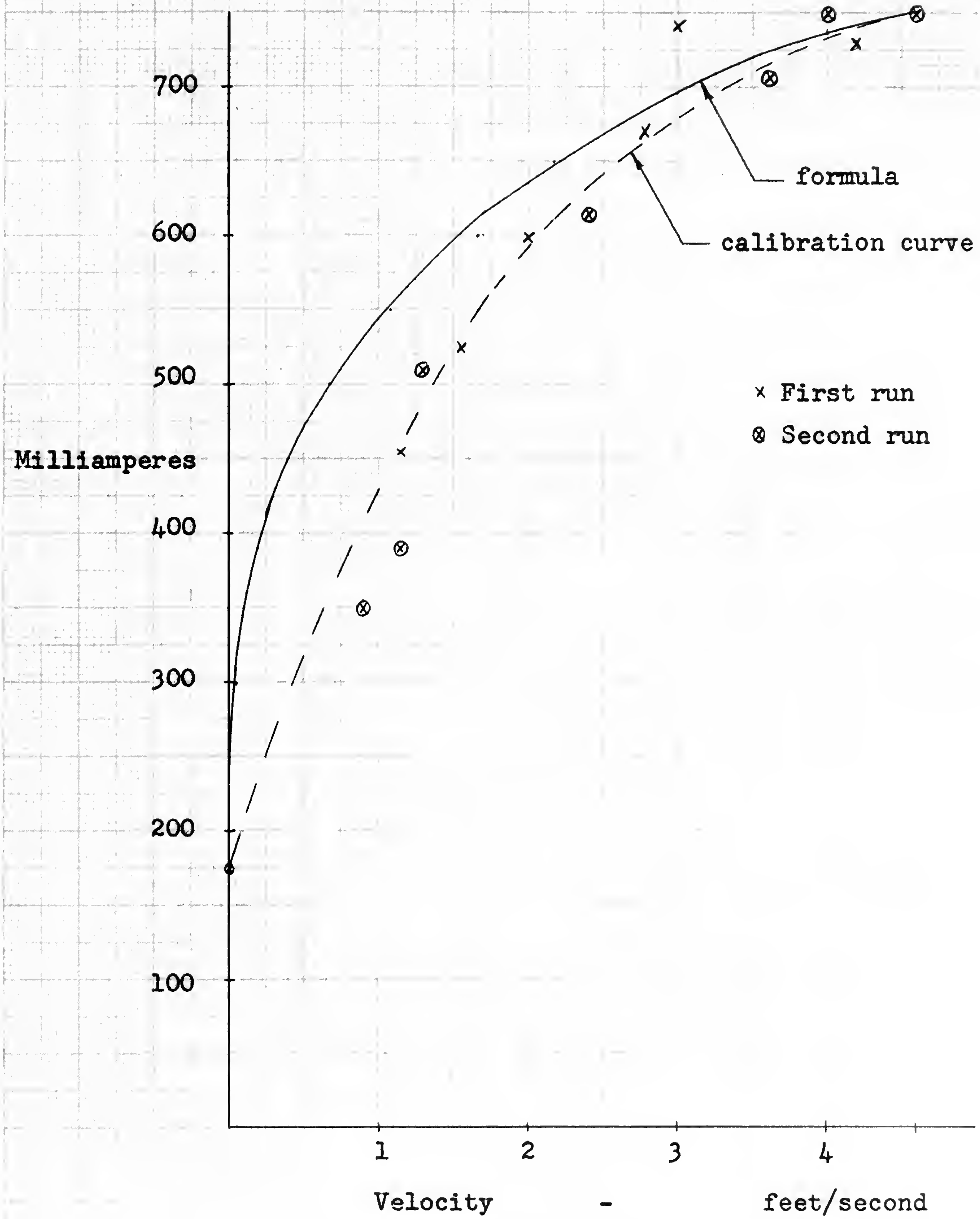


FIGURE 6. Calibration Curve

The thermal time constant of the hot wire was tested using a square wave current source circuit shown in Figure 7. This circuit provided 250 ma of current which heated the wire 25 degrees, causing a resistance change of .19 ohms.

The voltage across the wire was amplified by a D.C. amplifier having a time constant of 3 microseconds. The resulting wave form, inducting the thermal time constant, is shown in Figure 8.

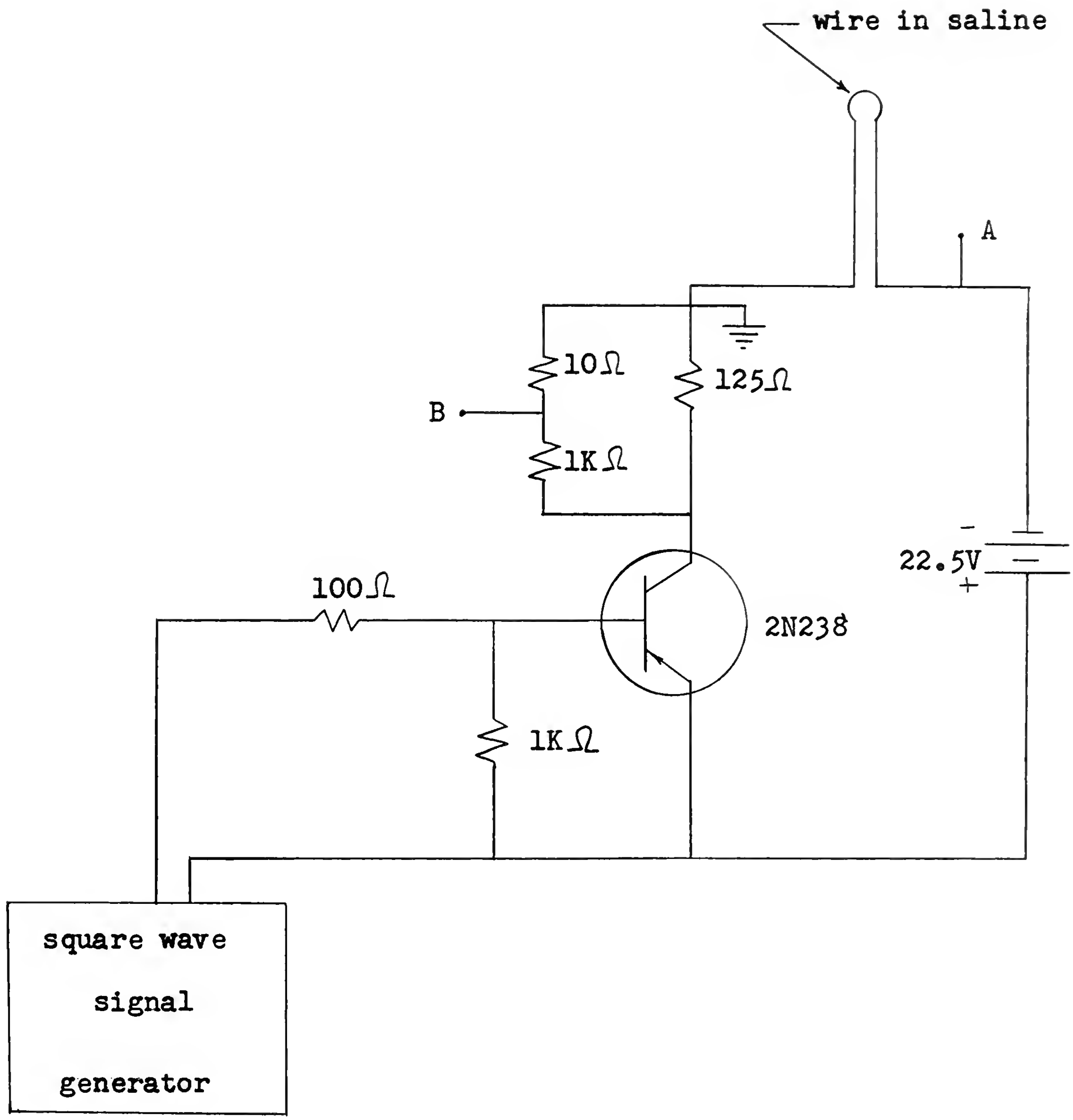
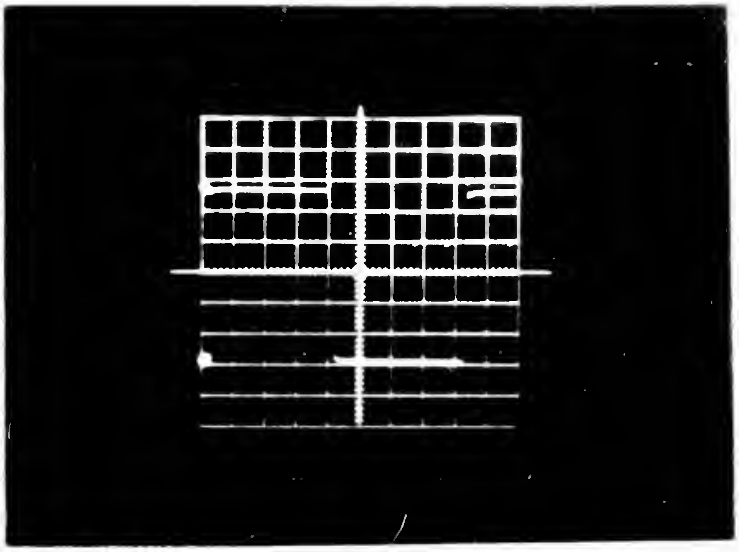
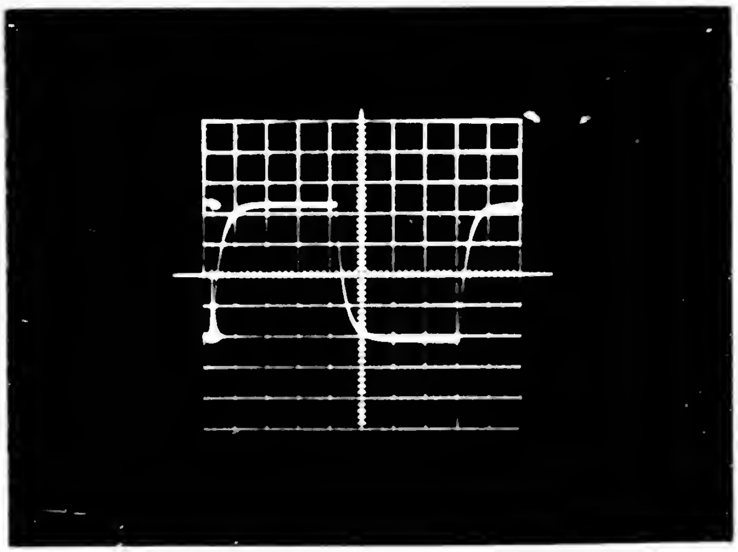


FIGURE 7. Thermal Time Constant Test Circuit



Voltage waveform at point B
Scale: 0.5 milliseconds per division



Voltage waveform at point A
showing thermal time constant
Scale: 0.5 milliseconds per division

FIGURE 8. Thermal time constant displayed on oscilloscope

CHAPTER III RESULTS

A complete working model of a blood flowmeter suitable for actual use was designed, constructed, and tested. The equipment appeared to work satisfactorily in all respects. The tests were conducted only in water. The calibration of current verses velocity is shown in Figure 6. The calibration curve shows general agreement with the predicted curve. Some deviation from the predicted curve can be expected due to the design of the probe which causes the hot wire to be situated in the region of a developing boundary layer. The variation at low velocity was due to difficulty in accurately determining the turntable speed in this velocity range.

The thermal time constant of the hot wire, which determines the frequency capabilities of this device, is shown in Figure 8. The 0.25 millisecond thermal time constant is in fair agreement with calculations and permits frequencies of up to 636 cps to be recorded.

CHAPTER IV CONCLUSION

The use of a constant temperature hot wire anemometer has been found to be a practical method for determining fluid velocity and can be used in certain parts of the body. The problem of calibrating such an instrument is not difficult in the laboratory, however it has not yet been shown how this calibration will compare with measurements _in vivo_. Each catheter probe must be individually calibrated to account for any physical differences in construction. The amplifier circuit must be well shielded and a high quality D.C. operational amplifier is required.

CHAPTER V RECOMMENDATIONS

It is recommended that the following areas be investigated:

1. Design of a similar system that does not require a D.C. amplifier in order to avoid the noise inherent in such amplifiers.
   A system using an A.C. bridge with D.C. feedback might be workable.
2. Further investigation into probe design to permit measurement of flow before the flow is materially disturbed.
3. Design and construction of additional circuitry to provide linearization of the output versus flow to provide easier interpretation of data.
4. Investigation of methods for verification of frequency response of entire system.
5. Comparison of the calibration curve obtained in the laboratory with measurements *in vivo*.

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